Modelling Streamflow Reduction Impacts of Commercial Afforestation and Invasive Alien Vegetation in Complex River Systems

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ABSTRACT

The National Water Act (No.36 of 1998), allows the minister (DWAF) to regulate land-based activities, which reduce streamflow, by declaring such activities to be streamflow reduction activities (SFRAs). Commercial afforestation has been declared a SFRA in terms of the Act. A form of landuse that is not a declared SFRA, but which has a similar impact as afforestation, is that of invasion by alien plants. It is widely accepted that streamflows can be significantly reduced by the invasion of riparian zones and hillslopes by alien vegetation.

In South Africa two basic methods of SFR estimation have been developed for these two landuse forms. These are:

1. Free-standing empirical relationships in the form of the CSIR SFR curves.
2. Component modules in the physically-based, land-use sensitive ACRU rainfall-runoff catchment model.

The empirical relationships have been used in conjunction with the monthly Pitman catchment model, while the ACRU model operates on a daily time step and finer spatial scale than the Pitman model. There is a need for a comparison of the outcomes of the two SFR estimation procedures and the development of guidelines describing when it is appropriate to use each method in a water resource evaluation setting.

The SFR estimation methods have been used in studies to determine the potential impacts of SFR due to commercial afforestation and alien vegetation on MAR, but, with the exception of a few ad hoc studies (Larsen *et al* 2001; Le Maitre and Görgens, 2001), there has been no systematic research into SFR impacts on utilisable water. There is a need for an assessment of the impacts of SFR, as estimated with the two SFR estimation methods, on reservoir yield and run-of-river supply.

This paper describes the process followed in arriving at estimates of SFR, and the associated impact on yield, produced by the two methods for different bioclimatic conditions, and outlines the findings of the process. The methods of SFR estimation were applied to three catchments representing different bioclimatic conditions in South Africa; the Berg, Sabie and Mhlatuze catchments. The output from the methods was run through the Water Resources Yield model to establish the impacts, on reservoir yield and run of river yield, of SFR estimated with the different models.

Keywords: *commercial afforestation, invasive alien plant, hydrological modelling, streamflow reduction, yield*

1 INTRODUCTION

Experiments conducted on afforested catchments in South Africa have shown that alien trees can cause substantial reductions in catchment runoff (Scott et al, 2000). At the national scale it is estimated that alien vegetation, in the form of commercial afforestation and invasive alien plants (IAPs), reduces South Africa's runoff by 2900 million m^3 per year, approximately 6% of the country's mean annual runoff (MAR) (DWAF, 2004).

In recognition of the impact which alien trees can have on the country's water resources, commercial afforestation was declared a stream flow reduction activity (SFRA) in terms of the National Water Act (NWA) (No. 36 of 1998), and the Department of Water affairs and Forestry (DWAF) launched the Working for Water Program (WfW) in 1995 with the recovery of water resources lost to IAPs as one of the Program's objectives. These initiatives have intensified the need to quantify SFR; for example, for licensing purposes to satisfy the requirements of the NWA and for predicting the effects of IAP clearing by WfW projects. Of interest to water resources practitioners, is the impact of SFR on mean annual runoff (MAR), on low flows and on water resource system, or reservoir, yield.

In South Africa two basic methods of streamflow reduction (SFR) estimation have been developed for commercial afforestation and IAPs. These are

- Free-standing empirical relationships in the form of the CSIR SFR curves, used in conjunction with the monthly, calibration-based, Pitman model.
- Component modules in the physically-based, land-use sensitive ACRU rainfall-runoff catchment model, run at a daily time step with relatively fine subcatchment delineation.

There is a need for an assessment and comparison of the impacts of SFR estimated via the two SFR estimation methods, in terms of impacts on total and low flow MAR and on system or reservoir yield. This study aims to meet this need by using both methods to estimate SFR for a number of commercial afforestation and IAP scenarios in three study systems representing different bioclimatic conditions in South Africa, and running the output from the SFR estimation methods through the Water Resources Yield Model (WRYM) to determine the impact of the SFR on yield. The analysis differentiates between upland and riparian SFR, where the riparian zone is described as 30 m wide strips on either side of the river centre line (Scott and Smith, 1997). The analysis also differentiates between SFR produced by different classes of tree (i.e. tall trees, which grow to greater than 8m in height; medium trees, which grow to taller than 2m; and tall shrubs, which grow to taller than 1.5m).

2 MODELS USED IN THE STUDY

2.1 SHELL

SHELL (Berg *et al*, 1991) is a user interface, which facilitates the use of a number of component programs at a monthly temporal resolution. SHELL allows a sequence of operations (programs) that describe all major water use in a catchment (including dam operations), to be set up and saved as a configuration file, and links the component programs to their data files.

The Pitman model is the catchment model used for runoff simulation in the SHELL. It is a parameter-fitting model, where the subcatchment physical characteristics are coarsely represented by a number of calibration parameters, the values of which are adjusted to obtain a simulated monthly flow sequence, similar to an observed monthly flow sequence at the outlet of the subcatchment

Afforestation-related SFR is estimated in SHELL using the program Forestry. This program is based on the empirical SFR functions / curves developed by the CSIR (Scott and Smith, 1997*)* to calculate SFR resulting from afforestation. The CSIR curves, are based on data derived from catchment experiments, conducted in different bioclimatic regions of South Africa, however the available experimental catchments all have MAP greater than 1 100 mm, representing less than 30% of afforested area MAPs in South Africa (Scott *et al*., 2000). The curves express percentage reduction in long-term mean total annual flow, or low flow, as a function of plantation age, with low flows defined as monthly flows exceeded 75 % of the time (Scott and Smith, 1997). The curves distinguish between pines and eucalypts, and optimal and sub-optimal tree-growing sites.

Upland IAP-related SFR is estimated in SHELL using the program Alien Veg. This program is based on the empirical Age-Biomass-SFR model developed by the CSIR (Le Maitre and Görgens, 2001) to calculate SFR resulting from invasion by alien vegetation. The model relates SFR to biomass, which in turn is related to tree age. The relationships were developed for the three tree classes, tall trees, medium trees and tall shrubs. Tree age is then related to a percentage reduction in annual total and low flow taking into consideration whether the streamflow from the catchment has a long or short lag response to water use by trees. The age-biomass-SFR relationships were based on a combination of data from catchment experiments and information from literature on the topic.

Riparian IAP-related SFR is estimated for use in SHELL using the Potential Evapotranspiration (PET) method (Dzvukamanja *et al*, 2005). This method is based on the assumption that maximum potential SFR due to riparian trees is equal to potential evapotranspiration by the trees, because riparian plants have direct access to water in the stream or to lateral interflow from upland hill slopes adjacent to the riparian zone. Transpiration by riparian plants is therefore limited by evaporative demand, plant physiology and availability of water from both the upstream subcatchments and the upland area of the subcatchment in question. The PET method uses A-pan evaporation measurements as an index of evaporative demand and crop coefficients (Smithers and Schulze, 1995) to represent the limiting effect of plant physiology. The relevant equations are as follows:

$$\text{Potential SFR} = \text{Potential ET}_{\text{alien vegetation}} - \text{Potential ET}_{\text{natural vegetation}} \quad (1)$$

$$\text{Potential ET} = \text{A-pan evaporation} \times \text{Crop coefficient} \quad (2)$$

The actual SFR is equal to the portion of potential SFR, which can be met by streamflow arriving at that point in the stream.

2.2 ACRU

ACRU is a physically based catchment model based on multi-layer soil water budgeting. The model uses input variables estimated from the physical characteristics of the catchment. Input into ACRU includes rainfall, evaporation, soil properties and land-use information. ACRU operates at relatively fine temporal and spatial resolution, using a daily time step and small subcatchment delineation. It is recommended that subcatchments in ACRU configurations do not exceed 50 km^2 (Smithers and Schulze, 1995). Included in the ACRU Model are various simulation options, including routines for reservoir water balance, irrigation demand and simulation of riparian processes

In ACRU, water use of plants is estimated using parameters, which describe the consumptive use characteristics of the plant species, and SFR by plants is a function of the consumptive use of the plants and the runoff generating properties of the soil. Parameters which affect the water use of plants include the crop coefficient, canopy interception loss, fraction of root system in each soil horizon and the fraction of the plant available water of a soil horizon at which total evaporation by the plant is assumed to drop below maximum evaporation during drying of soil.

Enhanced riparian water availability is modelled in ACRU by routing not only the surface and near surface flow from contributing areas into the riparian subcatchment as storm flow, but also the base flow from the associated upland subcatchment into the lower soil horizon of the riparian subcatchment as sub-surface flow. The sub-surface flow into the riparian zone first "fills" the lower soil horizon to saturation. Once that is exceeded, then the upper soil horizon is filled, and should that reach saturation, the excess water overflows from the soil, and is aggregated to the stormflows from the catchment. This increased soil moisture in the riparian zone is then available to the vegetation for plant water use

2.3 WRYM

WRYM is the river system model used in the study. The model is used for assessing the long term yield capabilities of a system for a given operating policy. It is used to analyse systems at constant development levels, i.e., the system components and the system demands remain constant throughout the full simulation period (DWA, 1987).

3 STUDY SYSTEMS

The catchments selected for the analysis were the Upper Berg in the Western Cape, the Upper Sabie in Mpumalanga and the Mhlatuze in KwaZulu Natal. Figure 1 shows the location of the selected study systems and Table 1 gives a summary of the study system characteristics.

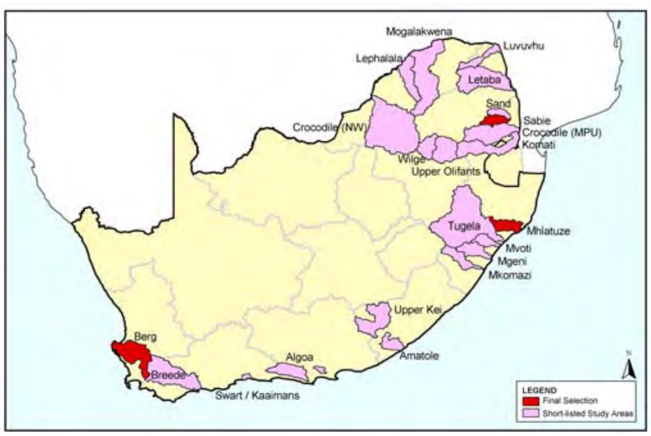

Figure 1: Location of study areas, showing short-listed areas and final selection

Table 1: Characteristics of study systems

Characteristic	Upper Berg	Upper Sabie	Mhlatuze
Total area (km^2)	620	1946	3628
Total afforestation (km^2)	81	781	531
IAP area - Total (km^2)	326	1946	3 098
IAP area - Condensed (km^2)	39	10	81
Total irrigated area (km^2)	34	76	151
Total farm dam storage 10^6m^3	16	6	40
Total large dam storage 10^6m^3	59	13.6	303

The study focuses on the Upper part of the Berg catchment, up to the town of Paarl. The Upper Berg catchment lies in the winter rainfall area, with cold, wet winters and hot, dry summers. The rainfall is heavily influenced by the mountains in the catchment, with the mountainous upper reaches having significantly higher MAPs than the lower lying areas and rain shadow areas. MAPs across the catchment range from 2 600 mm in the mountainous areas to 800 mm in the low-lying areas. (DWAF, 1997)
The Upper Sabie, modelled in this study, is upstream of the confluence with the Sand River. The Sabie River catchment has a warm to hot sub-tropical climate, with wet summers and dry winters. The rainfall season lasts from about November to March. The MAP in the catchment ranges from 2 000 mm in the high altitude areas towards the Drakensberg Mountains, to 600 mm in the lowveld areas. The rainfall is mainly due to thunderstorms, although orographic rain is common near the Drakensberg Mountain (DWA, 1990).

The Mhlatuze catchment has humid summers and relatively warm winters. Most rainfall occurs between January and May. Rainfall in winter is associated with frontal weather or moist air from the Indian Ocean Anticyclone. MAP ranges from about 1 200 mm at Richards Bay to below 900 mm at the top of the catchment (DWAF, 2003).

4 MODELLED SCENARIOS

Described below is the range of scenarios modelled. Each scenario was run for a 40 year period; The Upper Berg was modelled from 1952 to 1992, the Upper Sabie from 1956 to 1996 and the Mhlatuze from 1954 to 1994.

The baseline scenario represents the “natural” land cover as determined by SHELL. In SHELL, the following land and water uses are eliminated from the current scenario to provide the natural scenario:

- Irrigation and farm dams;
- Afforestation;
- Alien vegetation;
- Dryland sugarcane;
- Large reservoirs and bulk water abstractions;
- Water transfers into and out of the catchment; and
- Return flows / waste discharges.

Normally in ACRU modelling, the natural scenario is defined as the scenario which contains only Acocks land cover, however, because this study aims to compare the outputs from ACRU and SHELL, an attempt was made to create in ACRU, the same baseline found in SHELL. Hence, in the ACRU baseline, all land and water uses except the seven mentioned in bulleted points above, were left in the model. The seven excluded land and water uses were replaced with the relevant Acocks land cover. The residual land uses in the baseline scenario consist mainly of all dry land cultivation (except dryland sugarcane) and occasionally small semi urban areas.

The current scenario consists of the current (mid-1990s) mix of land cover and land and water use in the catchment.

In the “current scenario with forestry cleared,” the area covered by commercial forestry in the current scenario, is replaced with the relevant Acocks vegetation.

In the “current scenario with IAPs cleared,” the area covered by IAPs in the current scenario, is replaced with the relevant Acocks vegetation.

The upland IAP scenarios (upland tall trees, upland medium trees and upland tall shrubs) were created by replacing a portion of the natural area in the baseline scenario with an area of upland alien vegetation equal to the *invadable upland area* of the catchment. In this study, the invadable area for each subcatchment was defined as the current area not covered by man-made influences, i.e., the area not covered by irrigation, urbanisation, dryland cultivation, reservoirs or forestry.

For the riparian IAP scenarios (riparian tall trees, riparian medium trees and riparian tall shrubs), the complete riparian area in the baseline scenario is replaced with alien invasion and the upland is left in the baseline state.

The commercial afforestation scenarios (pine afforestation or eucalyptus afforestation) were created by replacing a portion of the upland area in the baseline scenario with an area of commercial afforestation equal to the current area of afforestation in the catchment. In this scenario, the residual upland is left in the baseline condition.

5 RESULTS OF SHELL CALIBRATION AND ACRU VERIFICATION

The calibration of SHELL and verification of ACRU were done for 10-year periods. The SHELL configuration was calibrated at a number of flow gauging stations within the catchment, while the ACRU configurations were verified using the most reliable flow gauging station within the catchment. The results of the calibration and verification are presented in Table 2 and Figure 2. The calibration of SHELL and verification of ACRU for the study systems produce different fits to the observed data from the two models. The MAR produced by SHELL is 9% greater than that produced by ACRU for the Upper Berg, 35% greater for the Mhlatuze and 17% less for the Upper Sabie. Since the two models are so different from each other, it was expected that the calibration and verification exercises would produce different results. The calibration of SHELL was heavily influenced by iterative patching of unreliable or missing observed flow data with simulated SHELL flows, particularly for the Sabie and Mhlatuze catchments, where 8% and 28%, respectively of the flow record over the calibration period was either missing or incomplete. Both models achieve reasonable average seasonal correspondence of high and low flows with the observed averages, however, for the Mhlatuze, the SHELL seasonal distribution was markedly different to that of the observed flow. This is attributed to the influence of iterative patching of the observed flow with the simulated SHELL flows on the SHELL output.

Table 2: Results of SHELL calibration and ACRU verification (10 year periods)

Catchment	Gauge	MAR						STANDARD DEVIATION				
		+Patched Obs	*Obs	ACRU	SHELL	%Difference (ACRU-*Obs)	%Difference (SHELL-Obs)	*Obs	ACRU	SHELL	%Difference (ACRU-*Obs)	%Difference (SHELL-Obs)
		(mm)	(mm)	(mm)	(mm)	(%)	(%)	(mm)	(mm)	(mm)	(%)	(%)
Berg	G1H020	637	595	638	695	7	17	136	104	129	-24	-5
Sabie	X3H004	85	61	100	83	63	35	48	100	88	106	82
Mhlatuze	W1H009	104	57	74	100	29	74	51	63	95	24	85

* unpatched observed flow data + patched with simulated SHELL values

6 COMPARISON OF BASELINE MAR AND LOW FLOW PRODUCED BY THE MODELS

Since the simulated flows related to the calibration and verification of SHELL and ACRU differ from each other, it follows that the baseline flows should also differ from each other. This can be seen in Table 3, which compares the incremental MAR produced by the different models for each study system. On average, the difference in simulated baseline MAR between the models is greater for low flows. On average, flows simulated by ACRU are lower than those simulated by SHELL, except for the Upper Berg, where low flow simulated by ACRU is much higher than that simulated by SHELL. The differences in baseline MAR produced by ACRU and SHELL imply that SFR estimated by ACRU cannot be compared meaningfully with SFR estimated by SHELL, in absolute (mm) terms, but a comparison on the basis of percentage of MAR should be meaningful.

Table 3: Baseline MAR produced by SHELL and ACRU for the study systems (40 year periods)

Catchment	Subcatchment name / number	Baseline MAR (mm)			Baseline Low Flow MAR (mm)			Standard Deviation in monthly runoff (mm)		
		SHELL	ACRU	(ACRU - SHELL)	SHELL	ACRU	%Difference (ACRU - SHELL)	SHELL	ACRU	%Difference (ACRU - SHELL)
Upper Berg (total catchment)	G1H020	780	705	-10	14	43	207	73	48	-34
Upper Sabie (total catchment)	30	263	216	-18	17	3	-85	29	34	16
Mhlatuze (total catchment)	W12H	259	223	-14	8.1	5.6	-32	37.5	36.6	-2
Mhlatuze (incremental catchments)	w12A	125	125	0	6.7	2.7	-59	17.8	16.7	-6
	W12B	151	199	32	8.2	9.0	10	23.4	26.2	12
	W12C	196	161	-18	6.6	5.6	-15	28.1	23.3	-17
	W12D	186	175	-6	5.0	4.3	-14	31.0	26.5	-14
	W12E	311	300	-4	8.4	11.5	36	43.6	38.5	-12
	W12F	300	320	7	11.4	14.1	23	51.4	33.8	-34
	W12G	201	173	-14	5.5	2.3	-58	34.7	30.8	-11
	W12H	298	257	-14	9.2	7.0	-24	41.6	41.7	0

7 COMPARISON OF MODELLED SFR WITH MEASURED SFR

SFR estimated by ACRU and SHELL was compared with measured SFR from the South African catchment experiments (Scott *et al*, 2000). Table 4 presents the mean annual total SFR measured for eight of the experimental catchments treated with pine in the upland areas only. Table 5 presents mean annual total SFR simulated by ACRU and SHELL. The SFR has been presented for a number of subcatchments in the Mhlatuze, whereas for the Upper Berg and Upper Sabie, the SFR has been presented for the total catchment. This was done to save on time and resources. The SFR in the tables has been expressed as SFR in mm per 10% of catchment treated and SFR in % MAR per 10% of catchment treated, to enable comparison between catchments with different areas of afforestation and different MARs.

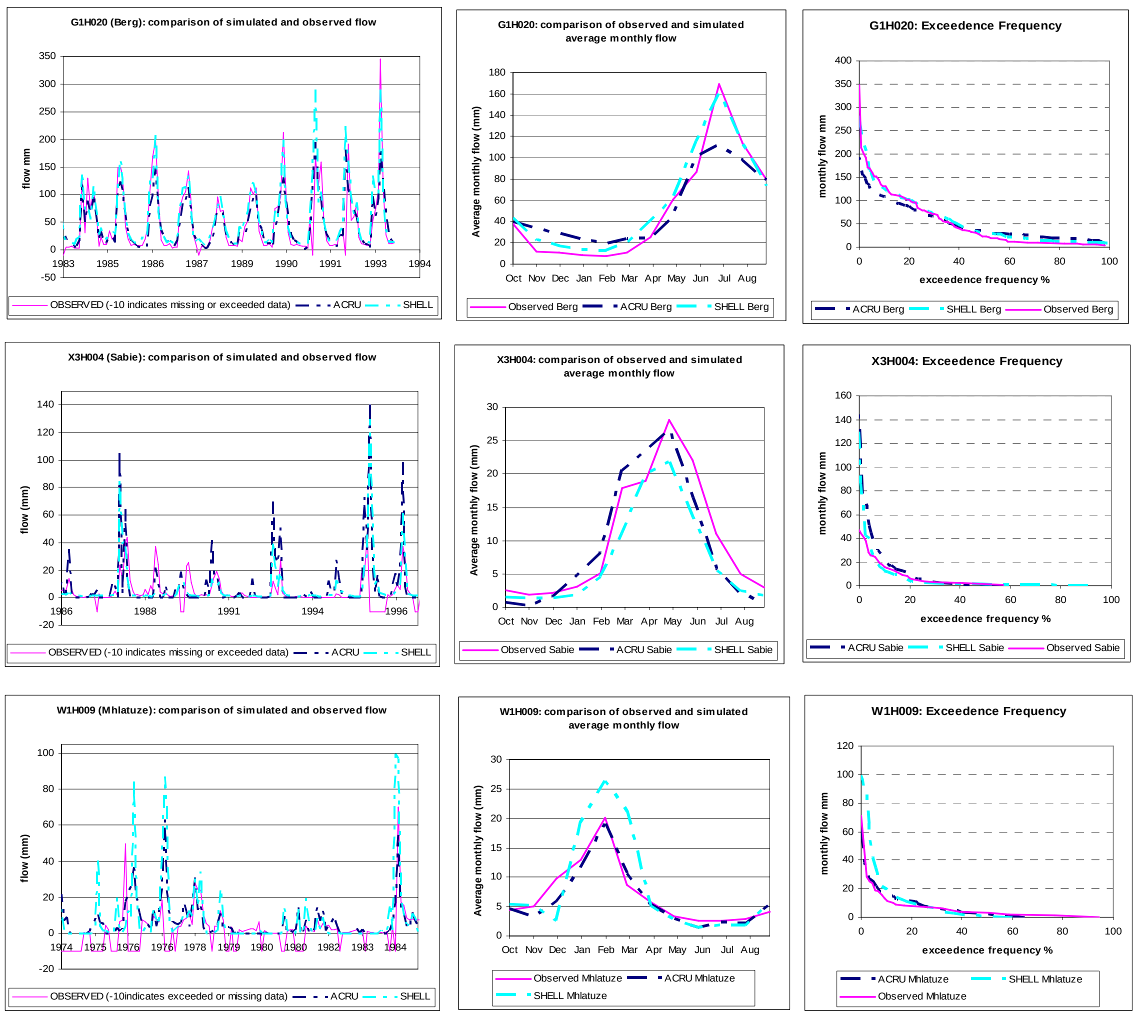

Figure 2: Results of SHELL calibration and ACRU verification

The tables show that the absolute SFR (mm per 10% treated) simulated by the models is generally lower than that measured at the experimental catchments. While some of the SHELL SFRs fall within the range of experimental catchment SFRs, the ACRU SFRs are extremely low compared to the experimental SFRs. The SFR simulated by SHELL is expected to bear a sound resemblance to the measured SFR, since the SFR estimation curves used in SHELL are based on data from the experimental catchments. The fact that the simulated SFRs, especially the ACRU values, are lower than the measured may be explained by variations in conditions between the experimental catchment sites and the simulated catchment. For example, the experimental catchments are all located in high rainfall regions with MAPs greater than 1100 mm, whereas the MAPs of most of the simulated subcatchments are well below 1100 mm. The SHELL figures (in mm per 10% of catchment treated) for the Upper Berg catchment and Mhlatuze catchments W12F and W12H, with high MAPs similar to those of the experimental catchments, resemble those of the experimental catchments. As well as MAP, the ACRU results are also determined by the choice of baseline vegetation.

As a proportion of MAR, the SHELL SFR is actually higher than the SFR of most of the experimental catchments in the table. The ACRU SFRs are still lower than those of the experimental catchments, when looked at proportionally; however, they are now closer to the order of magnitude of the proportional reductions of the experimental catchments. This indicates that the relative degree of wetness of the catchment has a strong influence on the amount of SFR caused by trees.

The SHELL-estimated SFRs are based on the CSIR curves, which were derived from data sourced from experimental catchments with relatively humid conditions, where soil water stress plays a minor role. In the modelled catchments, soil water stress occurs more often than in the experimental catchments, therefore SHELL can be expected to over-estimate SFR for the modelled subcatchments. The physically-based ACRU-estimated SFRs therefore appear low in contrast to the SHELL values. Also, in ACRU, total evaporation by plants drops below maximum evaporation during drying of the soil. The point at which this happens is governed by the ACRU parameter CONST, which represents the fraction of plant available water at which total evaporation drops below maximum evaporation during drying of the soil. Plants with higher values of the parameter CONST are more conservative water users than plants with lower CONST. Pines are modelled with a relatively high value for CONST (0.9). This contributes to the lowness of SFR estimated by ACRU for pines.

Table 4: SFR recorded from the South African catchment afforestation experiments (Scott *et al*, 2000)

	Experimental catchment	**Pre-treatment MAR (mm)**	**MAP (mm)**	***Average age (years)**	**% of catchment treated**	**Mean annual total SFR (mm)**	**Mean annual total SFR (mm per 10% of catchment treated)**	**Mean annual total SFR (% of MAR per 10% of catchment treated)**
Winter rainfall region	Bosboukloof	246	1100	18	57	150	26	11
	Tierkloof	1077	1300	18	36	109	30	3
	Lambrechtsbos B	518	1100	16	82	169	21	4
	Lambrechtsbos A	564	1100	10	89	205	23	4
Summer rainfall region	Catchment 2, Cathedral Peak	807	1400	15	75	297	40	5
	Catchment 3, Cathedral Peak	683	1400	11	86	184	21	3
* Average age over the SFR record period								

Table 5: SFR due to pine afforestation estimated by ACRU and SHELL for the upland pine scenario

Simulated subcatchment	**Baseline Mar (mm)**		**MAP (mm)**	**Average age (years)**	**% of catchment afforested**	**mean annual total SFR (mm)**		**Mean annual total SFR (mm per 10% of catchment treated)**		**Mean annual total SFR (% of MAR per 10% of catchment treated)**	
	SHELL	**ACRU**				**SHELL**	**ACRU**	**SHELL**	**ACRU**	**SHELL**	**ACRU**
MHLATUZE											
W12A	125	125	876	11	30	27	7	9	2	7	2
W12B	151	199	934	11	8	9	0	11	0	7	0
W12C	196	161	848	11	25	35	8	14	3	7	2
W12D	186	175	847	11	2	2	1	14	4	7	2
W12F	300	320	1247	11	9	19	4	22	5	7	2
W12H	298	257	1043	11	27	57	9	21	3	7	1
BERG											
G1H020	780	705	1196	16	13	53	6	41	4	5	1
SABIE											
30	263	216	873	11	44	97	0	22	0	8	0

8 ASSESSMENT OF SFR PRODUCED BY ACRU AND SHELL

A sample of results for the ACRU and SHELL SFR modelling exercise is presented in

Table 6 and

Table 8. The SFR results can be summarised as follows.

8.1 ACRU Modelling

ACRU modelling of the scenarios produced some *unexpected* results as follows:

- Tall shrubs, which intuitively can be expected to cause little SFR, cause greater reduction in total MAR than medium trees in both the upland and riparian situations in the Mhlatuze catchment. Riparian tall shrubs also cause slightly more reduction in low flow MAR than Riparian tall trees in the Mhlatuze.
- Different proportional reductions in MAR and low flow MAR were estimated for the same tall tree species in the same subcatchment, because the different areas under trees considered resulted in different compositions of natural vegetation replaced.
- Gains in low flow MAR are simulated for the replacement of natural vegetation with pine trees. This is because when pine trees experience water stress in the dry season, total evaporation by the trees drops well below maximum evaporation. This leads to water use by pines being lower than that of the natural vegetation being replaced, during periods of the dry season. The subcatchment soil properties can influence the severity of the low flow gains in SFR.

Expected outcomes of the ACRU modelling include the following:

- Proportional reduction in MAR by tall trees is greater than by medium trees and tall shrubs in both the upland and riparian situations.
- Proportional reduction in MAR and low flow MAR by riparian IAPs is greater than for upland IAPs.
- The seasonal distribution of upland SFR follows the same trend as natural runoff with highest absolute SFR in the high flow season and lowest absolute SFR in the low flow season. The seasonal distribution of riparian SFR is the opposite, with highest absolute SFR in the low flow season and lowest absolute SFR in the high flow season.
- Percentage reduction in low flow MAR is generally higher than percentage reduction in total MAR.

8.2 SHELL Modelling

Generally, the results produced by the SHELL modelling were as *expected* from the input data used to produce them. These include:

- Reduction in total and low flow MAR in the upland situation is greater for tall trees than for medium trees and greater for medium trees than for tall shrubs.
- The comparative effect of pine afforestation and eucalyptus afforestation depends on the rotation chosen for the trees for use with the CSIR curves.
- Riparian tall trees cause a greater reduction in total and low flow MAR than riparian medium trees, which in turn, cause greater reductions than riparian tall shrubs. This outcome depends on the crop coefficients used to estimate the SFR.
- Riparian IAPs cause greater proportional reduction in total and low flow MAR than upland IAPs.
- The seasonal distribution of upland SFR follows the same trend as natural runoff with highest SFR in the high flow season and lowest SFR in the low flow season. The seasonal distribution of riparian SFR is the opposite, with highest SFR in the low flow season and lowest SFR in the high flow season.
- Percentage reduction in low flow MAR is generally higher than percentage reduction in total MAR, all else being the same.

8.3 Interpreting the Effects of Bio-climatic Variations

The effects of bio-climatic variations on the results of the SFR modelling with ACRU and SHELL raised the following insights:

- The rainfall region, whether winter or summer rainfall, affects the seasonal distribution of SFR produced and also affects the growth condition of afforestation for use with the CSIR curve.
- The types of natural vegetation and IAPs dominant in the region determine the difference in water use between the IAPs or afforestation and the natural vegetation they replace. This has a large influence on SFR.

9 IMPACT ON YIELD

The impact of ACRU- and SHELL-modelled SFR on yield of a given assurance was determined for reservoir yield and run-of river yield for 40 year flow sequences. The firm yield (the annual volume of water, which can be supplied from the reservoir or river without failure for the given flow sequence) and the 1 in 5-year failure yield (the annual volume of water, which can be supplied by the reservoir or river with an 80% annual reliability of supply for the given flow sequence) were investigated for the total catchment and for smaller upstream subcatchments. Reservoir yield was determined for a 1 MAR hypothetical reservoir situated at the end of the catchment in question. Due to time and resource constraints, only the total catchment firm yield was determined for the Upper Berg and Upper Sabie, while the full range of scenarios was run for the Mhlatuze. The impact of SFR on yield was assessed using the ratio of percentage reduction in yield to percentage reduction in MAR

The ratios of reduction in yield to reduction in MAR for the three total catchments were averaged, as shown in Table 10. From Table 10, the results of the yield modelling exercise, in terms of the impacts of SFR on yield at a given assurance, are summarised as follows:

- On average:
  - via ACRU, ratios of impact are greater than one.
  - via SHELL, ratios of impacts are greater than one, except for the reservoir 1 in 5-year ratio, which is equal to one.
- On average:
  - via ACRU, the impact on run-of-river firm yield is smaller than the impact on run-of-river 1 in 5-year yield, whereas the impact on reservoir firm yield is greater than the impact on reservoir 1 in 5-year yield.
  - via SHELL, the impact on firm yield is greater than the impact on 1 in 5-year yield for both run-of-river and reservoir yield.
- On average:
  - The impact on run-of-river firm yield via ACRU is smaller than via SHELL.
  - The impact on reservoir firm yield via ACRU is greater than via SHELL.
  - The impact on run-of-river 1 in 5-year yield, via ACRU, is similar to via SHELL.
  - The impact on reservoir 1 in 5-year yield, via ACRU, is greater than via SHELL.
- On average, the impact on reservoir yield is smaller than on run-of-river yield

It was also observed that impacts on yield at upstream subcatchments in a catchment tend to be larger at upstream subcatchments

Table 6: SFR simulated for upland scenarios in subcatchment W12F at the flow exit point of the Mhlatuze catchment

Scenario	Baseline MAR (mm)	Baseline low flow MAR (mm)	Reduction per 10% of catchment treated: Reduction in baseline MAR (mm)	Reduction in baseline low flow MAR (mm)	Reduction in baseline MAR (%)	Reduction in baseline low flow MAR (%)
ACRU						
upland tall trees	319.6	14.1	14.6	0.5	4.6	3.8
upland medium trees			5.8	0.5	1.8	3.3
upland tall shrubs			10.6	0.4	3.3	2.9
commercial pine			4.9	-0.3	1.5	-1.8
commercial eucalyptus			16.8	0.6	5.2	4.0
SHELL						
upland tall trees	300.1	11.4	21.4	0.9	7.1	7.4
upland medium trees			16.3	0.7	5.4	6.1
upland tall shrubs			6.4	0.3	2.1	2.6
commercial pine			21.6	0.9	7.2	7.6

Scenario	Baseline MAR (mm)	Baseline low flow MAR (mm)	Reduction per 10% of catchment treated			
			Reduction in baseline MAR (mm)	Reduction in baseline low flow MAR (mm)	Reduction in baseline MAR (%)	Reduction in baseline low flow MAR (%)
commercial eucalyptus			19.5	0.8	6.5	7.3

Table 8: SFR simulated for riparian scenarios in subcatchment W12F at the flow exit point of the Mhlatuze catchment

Scenario	Subcatchment Grouping		Total Flow					Low Flow				
	Incremental	Cumulative	Baseline Catchment MAR (10^6m^3)	Unit reduction: Riparian strip MAR (mm)	Unit reduction: Equivalent Upland MAR(mm)	Reduction: Catchment MAR (10^6m^3)	Reduction: Catchment MAR (%)	Baseline Catchment Low Flow MAR (10^6m^3)	Unit red.: Riparian strip Low Flow MAR(mm)	Unit red.: Equivalent Upland Low Flow MAR(mm)	Reduction: Catchment Low Flow MAR (10^6m^3)	Reduction: Catchment Low Flow MAR (%)
ACRU												
riparian tall trees	Inc		53.4	272.6	146.4	1.4	2.7	2.4	81.8	5.4	0.4	18.2
		Cum	706.2			46.5	6.6	29.0			9.1	31.4
riparian medium trees	Inc		53.4	211.0	57.8	1.1	2.1	2.4	35.6	4.6	0.2	7.9
		Cum	706.2			30.5	4.3	29.0			7.3	25.2
riparian tall shrubs	Inc		53.4	267.5	106.0	1.4	2.6	2.4	72.8	4.1	0.4	16.2
		Cum	706.2			44.5	6.3	29.0			9.1	31.5
SHELL												
riparian tall trees	Inc		50.1	810.3	213.7	4.2	8.5	1.9	389.6	8.5	2.0	106.9
		Cum	728.9			126.7	17.4	32.4			27.1	83.5
riparian medium trees	Inc		50.1	547.6	162.6	2.9	5.7	1.9	202.1	7.0	1.1	55.4
		Cum	728.9			86.7	11.9	32.4			22.3	68.8
riparian tall shrubs	Inc		50.1	220.0	64.1	1.2	2.3	1.9	26.1	2.9	0.1	7.1
		Cum	728.9			32.9	4.5	32.4			8.9	27.4

Table 10: Summary of average ratios of reduction in yield to reduction in MAR for total study systems

	Average ratios for afforestation and IAPs			
	Reservoir yield		Run-of-river yield	
	Firm	1:5 year	Firm	1:5 year
ACRU	1.3*	1.1	2.5	5.0
SHELL	1.2	1.0	6.2	5.0
Average	1.2	1.0	4.3	5.0

*Outliers were excluded from this average

There were a few ACRU scenarios where the ratio of reduction in yield to reduction in MAR was negative, i.e. a reduction in MAR translated to a gain in yield and vice-versa. To explain these anomalies, the monthly volume of water in the yield reservoir for the baseline scenario was compared to the monthly total SFR due to the afforestation in each of these scenarios. An example of such a comparison, where a gain in MAR of 0.2% translated to a reduction in yield of 3.9%, is shown in Figure 3 . The comparison shows that, whereas the reduction in MAR is influenced by alternating gains and reductions in streamflow (which cancel each other out when averaged), during the critical period (1981 to 1985), mostly reductions, and a few comparatively small gains in streamflow, influence the yield of the reservoir. This explains why, in this case, an average increase in MAR leads to a reduction in reservoir yield and why the reduction in yield is large compared to the increase in MAR. The nature of the SFR sequence during the critical period, and not the reduction in MAR, determines the impact of SFR on yield.

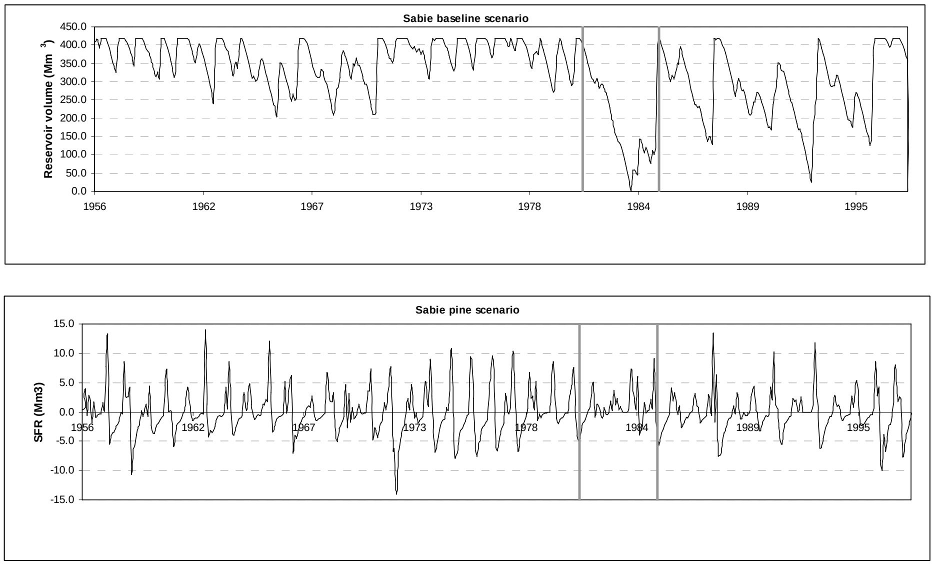

Figure 3: Comparison of Yield Reservoir Volume for the ACRU Baseline Scenario and SFR for the ACRU Pine Scenario for the Total Sabie Catchment

10 CONCLUSIONS AND RECOMMENDATIONS

The following are some of the conclusions drawn from the study:

1. In calibration of SHELL configurations and verification of ACRU configurations, both models are capable of achieving a reasonable average seasonal correspondence of high and low flows with the observed averages, though the actual averages produced by the two models can differ substantially.
2. MAR simulated by the models has a strong influence on SFR simulated by the models.
3. ACRU simulation produces much less SFR than SHELL simulation.
4. Gains in SFR after afforestation or invasion by IAPs may occur during dry periods. The simulation of this (in ACRU, or in the SHELL riparian SFR method) depends greatly on the selection of crop factors for the baseline vegetation.
5. Comparative SFR between different tree classes may vary depending on season and catchment conditions; for example, tall shrubs may use more water than medium trees or tall trees. This is also very dependent on crop factors chosen for the different tree species (in ACRU, or in the SHELL riparian SFR method).
6. In the assessment of impacts on yield, on average, impacts on yield by SFR due to IAPS and afforestation is greater than the impact on MAR. This indicates that the assessment of impact on yield is important in SFR analysis.
7. The impacts on yield at upstream subcatchments tend to be larger than the impact at the end of the e whole catchment.
8. A simulated reduction in MAR can result in a simulated increase in yield of a given assurance, if the portion of the flow sequence occurring during the critical period is dominated by streamflow gains; likewise, a simulated increase in MAR can result in a simulated reduction in yield of a given assurance, if the portion of the flow sequence occurring during the critical period is dominated by streamflow reductions.

Recommendations drawn from the study include the following:

1. If calibration-based models, like Pitman, are to be used extensively in water resources analysis, the availability of reliable observed streamflow data must be improved.
2. More field measurements of processes, which impact SFR, are required to gauge the performance of physical models (like ACRU) in simulating these processes. An example of this is the direct measurement of evapotranspiration by trees.
3. Improved (finer scale) mapping of vegetation types within catchments is required to capitalise more on models (like ACRU), which run at small spatial scales. This should also include the distinction between vegetation in riparian and upland areas of catchments, particularly vegetation for inclusion in model configuration baseline scenarios.
4. More rainfall gauging is necessary in high altitude catchments, to capture the correct rainfall patterns in catchments with steep MAP gradients, like the Upper Berg and Upper Sabie. Alternatively, relationships that translate rainfall information for the low altitude catchments to information for the high altitude catchments need to be developed.

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